35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Smart Textile Device Using Ion Polymer Metal Compound

Taro Nakamura and Tadashi Ihara, *Member, IEEE*

Abstract— **We have developed a smart textile device that detects angular displacement of attached surface using ion polymer metal compound. The device was composed of ion polymer metal compound (IPMC) which was fabricated from Nafion resin by heat-press and chemical gold plating. The generated voltage from IPMC was measured as a function of bending angle. Fabricated IPMC device was weaved into a cotton cloth and multidirectional movements were detected.**

I. Introduction

Ion polymer metal compound (IPMC) is a unique soft-actuator that achieves very fast response of bending deformation with low voltage. It also works as a sensor, that is, when the IPMC membrane is bent, it generates voltage across the membrane surface.

Numerous research works on the mechanism of IPMC as an actuator as well as its applications have been reported. Smart textiles, or a wearable, embedded sensor that monitors the motion, temperature, ECG, blood pressure and other parameters of wearing person is recently investigated widely. IPMC is expected to function as a smart textile device that detects directional motion of the outfit of a person.

The aim of this study is to clarify the basic characteristics of IPMC as a sensor and to develop prototype models of smart textile in which IPMC sensor unit detects angular displacement.

Our previous studies indicated: (1) the force generation of IPMC is proportional to the membrane thickness, the number of repetition of plating, and the pre-heating time. (2) The increase of force generation of IPMC is related to the increased membrane capacitance. (3) The membrane resistance of IPMC changes independent of the membrane capacitance. (4) IPMC membrane characteristics may be described fairly well with a simple RC equivalent circuit model.

Despite numerous works on the mechanism of IPMC as an actuator, the mechanism of IPMC as a sensor is yet fully understood. A significant difference between IPMC actuator and IPMC sensor is that the former required aqueous or saturated humidity while the latter operates in room or dry environment. Fundamental mechanical characteristics of the IPMC actuator operation are being investigated.

T. Nakamura is with the Department of Clinical Engineering, Suzuka University of Medical Science, Suzuka, MIE 5100293, JAPAN (corresponding author to provide phone: 303-555-5555; fax: 303-555-5555; e-mail: t-nakamu@suzuka-u.ac.jp).

T. Ihara is with the Department of Clinical Engineering, Suzuka University of Medical Science, Suzuka, MIE 5100293, JAPAN (corresponding author to provide phone: 81-59-383-8991; fax: 81-59-383-9666; e-mail: ihara@suzuka-u.ac.jp).

Our preliminary goal of this study is to study the basic characteristics of IPMC as a motion sensor and to build a prototype model of the IPMC embedded smart textile. Also, the mechanism of IPMC as a sensor is discussed.

II. Method

A. Fabrication of IPMC

IPMC was fabricated using modified standard method[6-7]. Nafion R-1100 resin was heat-pressed at 185 °C with 20-30 MPa. The thickness of IPMC was adjusted by changing the amount of resin, pressure, and time to heat-press. Immersion and reduction process was repeated up to 4 times to thicken the thickness of gold plate surface. Disk-shaped membrane was then immersed to hydrolysis solution using a mixture of dimethyl sulfoxide (DMSO), potassium hydroxide (KOH), and water. The pre-processed membrane was permeated in $[Au(phen)Cl_2]^+$ solution. After the immersion, the membrane was reduced with 5% Na_2SO_3 solution to perform gold plating (Fig.1). The membrane was cut into a rectangular shape to fit into the sensor unit. IPMC membranes of 180 μm were cut into 1 mm by 50 mm rectangular strips.

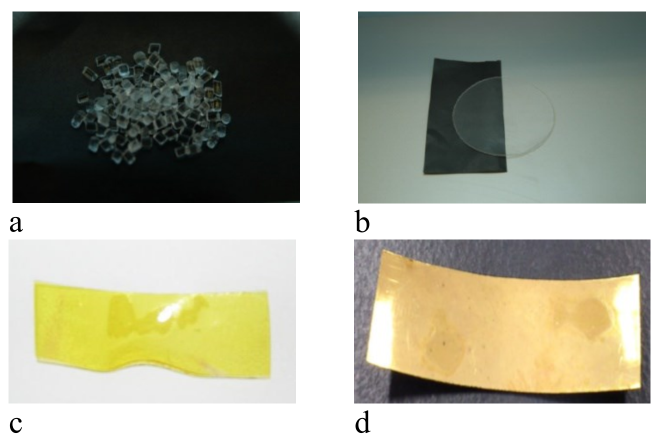

Fig. 1 Fabrication of IPMC a) Nafion resin b) after heat-press c) after immersion to $[Au(phen)Cl_2]^+$ solution d) after reduction

B. Measurement of Angular Displacement

The IPMC strip was placed in an angular displacement equipment and was manually bent up to 120 degree by 10 degree steps. Generated voltage was amplified by a differential amplifier (NF Corp. SA-400F3, SA-915D1) and recorded with an oscilloscope (Tektronix TDS 2002B).

C. Measurement of Inter-phalangeal Joint Movement

Prepared IPMC strip was weaved into a cotton glove and the angular movement by an index finger was measured.

978-1-4577-0216-7/13/$26.00 ©2013 IEEE

D. Measurement of Multidirectional Movement

4 IPMC strips were weaved into a cotton sheet and multidirectional movement was measured by these IPMC strips.

III. RESULTS

Fig. 2 shows the IPMC strip sensor units. And Fig.3 shows the sensing signal measurement system. IPMC membrane was clamped by a spring clip on which two electrodes are facilitated in order to supply voltage to IPMC. IPMC membrane was bent by an acrylic hinge that holds the membrane in set angle. The measurement system includes angular displacement unit, differential amplifiers and their power supply as well as oscilloscope that displays and records the measured signal. Fig.4 demonstrates the output signal from the IPMC sensor as function of angular displacement. Clearly linear relationship between the angular displacement and the sensed signal voltage is demonstrated. This linear relationship was demonstrated in wide variety of strip length, width as well as the thickness of IPMC strip.

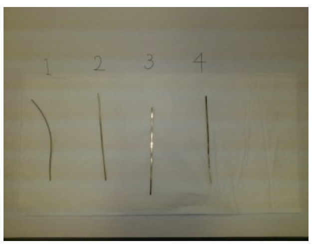

Fig.2 IPMC strip sensor

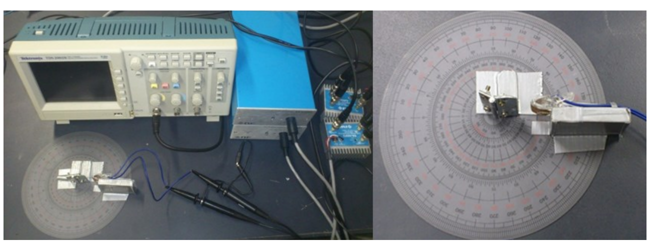

Fig.3 Angular displacement measurement system with a protractor base, an oscilloscope, two differential amplifiers and their power supply (left), the protractor base is magnified where the IPMC membrane is clamped by a spring clip and bent by an acrylic hinge that holds the membrane in set angle.

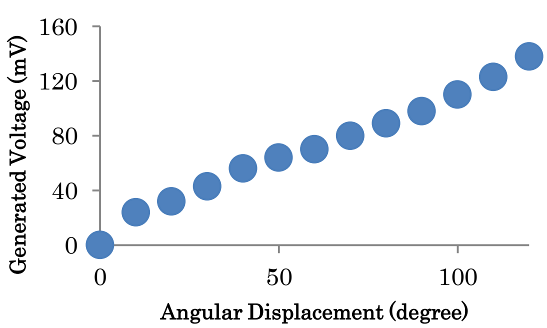

Fig. 4 Generated voltage from IPMC sensing unit as function of angular displacement

Fig. 5 shows a measurement of inter-phalangeal joint movement. IPMC sensor strip was embedded at the index finger part of the cotton glove. The index finger was bent up to 90 degree and the generated voltage was confirmed to show linear relationship with the bending angle as is the previous measurement of single strip (Fig.6).

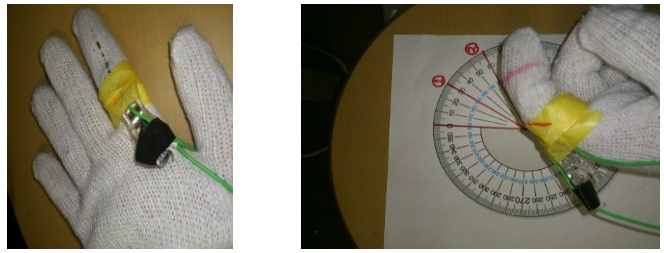

Fig.5 Measurement of inter-phalangeal joint movement: embedded IPMC sensor strip into the cotton glove (left) and the measurement of angular displacement (right)

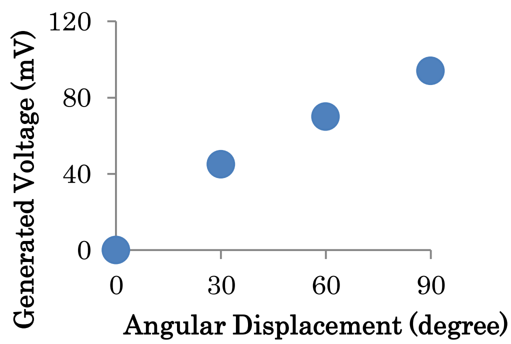

Fig. 6 Generated voltage by the embedded IPMC sensor strip into the cotton glove

Fig. 7 shows the setting of measuring multidirectional movement. Four IPMC strips were used to measure direction by 45 degrees. Fig. 8 is the recorded output voltage by the 4 IPMC strips. The results show that the IPMC strip placed parallel to the bending direction generates the maximum voltage while the one placed perpendicular to the bending direction generates no voltage. The IPMC strips placed 45 degrees to the bending direction showed generated voltage between the parallel strip and the perpendicular strip. The results demonstrates the capability of IPMS sensor strip to detect directional motions.

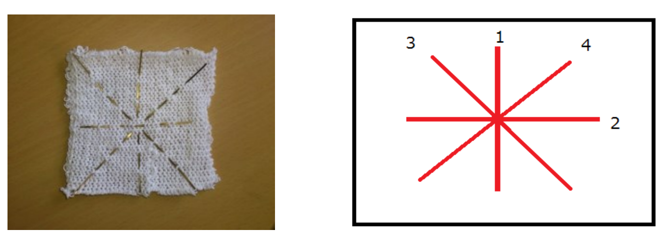

Fig. 7 Measurement of multidirectional movement: embedded IPMC sensor strips into cotton sheet (left) and a schematic diagram of 4 IPMC sensor strips for directional measurement

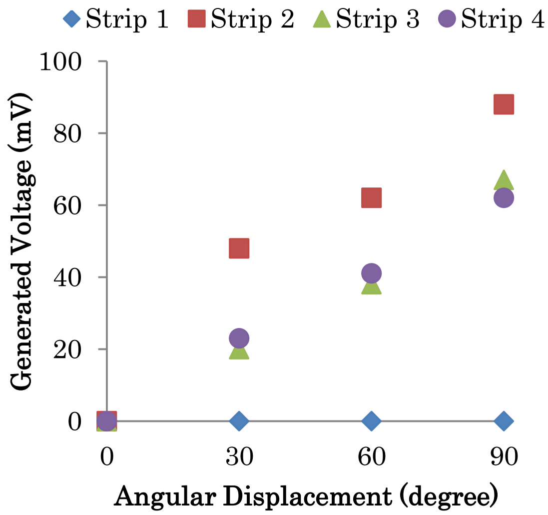

Fig. 8 Generated voltage by the embedded 4 IPMC sensor strips into the cotton sheet. Bending was applied along the strip 2 direction as shown in Fig.7.

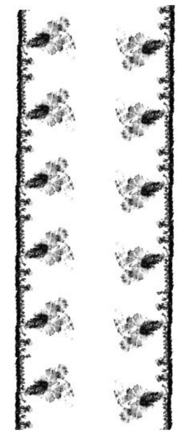

Fig.9 Schematic structure of IPMC: Nafion at the center is sandwiched by gold plating at both sides from which penetration of gold elements into Nafion is observed.

DISCUSSION

We have studied the basic characteristics of IPMC as an angular sensor and developed a prototype model of IPMC sensor unit that detects angular displacement.

IPMC demonstrated that its generated voltage by bending is almost linearly proportional to the angular displacement. Thus it is expected to be able to construct a unique reliable angular sensor with IPMC. It is still a preliminary study and further studies on the relationship of generated voltage as a function of remaining water content of IPMC, environmental humidity and temperature are needed.

In understanding the mechanism of IPMC as a sensor, we started from the several observations of IPMC as an actuator. Asaka et al[12-14] has demonstrated that IPMC is driven by the applied current rather than the electric field developed. Also, he suggests the mechanism of IPMC operation is described as the contraction at cathode and expansion at the anode side of the IPMC. Principal mechanism is supposed to be the movement of counter-ion accompanied by the trapped water molecule driven by the applied current at the both side of IPMC.

The electrode-Nafion boundaries are described as a complex fractal-like structure (Fig. 9). At the boundary surface, the electric double layer is formed and the principal electro-chemical behavior of IPMC is well described with a simple lumped resister-capacitor series circuit.

In our previous study, we have clarified that the increased membrane thickness increases the developed force of IPMC. Also, the repetition of plating increases the developed force by increasing the membrane capacitance. This would enable deeper penetration of electrode area into Nafion and shortens the effective inter-electrode distance which decreases the resistance across the Nafion layer. Longer pre-heating time also increased the capacitance and developed force. The effect of pre-heating may be attributed to the uniformarization and crystallization of Nafion structure as the Nafion resin melts in. These IPMC actuator mechanism characteristics would contribute in understanding IPMC sensor mechanism. However, it is hard to construct a model that explains the sensing mechanism as a whole based on these observations.

The more comprehensive IPMC mechanism model may apply to the analysis of sensor mechanism. In Asaka's model[13], The curvature of bending IPMC was modeled as a function of transmembrane current density:

$$\frac{1}{R} - \frac{1}{R_0} = \frac{f_1 j[1 - exp(-\upsilon t)] + M}{Q},$$

$$f_1 = \frac{d^3}{9} \frac{1}{1+H_{eq}} \frac{\phi \kappa E_m}{F D_m},$$

$$\upsilon = \left(\frac{1}{2d}\pi\right)^2 D_m,$$

$$M = \int_{-d}^{d} \pi(x,t) wx \, dx - [\gamma(d,t) R_f w d]$$

where $1/R$, E_m, d, H_{eq}, ϕ, κ, j, F, D_m, π, γ, R_f, and w denote curvature, the equilibrium bulk longitudinal modulus of the IPMC, thickness of IPMC as measured from the center, the equilibrium hydration, the water molar volume, the water transference coefficient in the IPMC, the current density, the Faraday constant, the diffusion coefficient, the osmotic pressure in IPMC, the interfacial tension between the membrane and the plated Au, the one dimensional roughness factor and the width of IPMC respectively.

Modifying the above equation, and relating the bending angle ϕ and IPMC membrane length L to the curvature, i.e., $\frac{1}{R} = \frac{2\phi}{L}$, we obtain:

$$j = \frac{\left(\frac{2\phi}{L} - \frac{1}{R_0}\right) Q}{f_1[1 - exp(-\upsilon t)] + M}.$$

Assuming that the current density is proportional to the generated voltage, the results supports this model in that the generated voltage shows proportional magnitude to the bending angle.

Further analysis of IPMC sensing mechanism will help bringing IPMC into practical use.

ACKNOWLEDGMENT

This work was support in part by Grants-in-aid for scientific research 16500305, 17040024, 19016021 Ministry of Education, Culture, Sports, and Technology, Japan.

REFERENCES

[1] Tadashi Ihara: Next Generation Medical Actuator Using Ion Polymer Metal Compound, Next-Generation Actuators Leading Breakthroughs, T.Higuchi, K.Suzumori, S.Tadokoro (Eds.), Springer, London, 2010.

[2] Ihara T, Ikada Y, Nakamura T, Mukai T, and Asaka, K (2006) Solid Polymer Electrolyte Membrane Flow Sensor for Tracheal Tube. Proc.SPIE 6167:61670U-1-61670U-8

[3] Ihara T, Nakamura T, Muka T, and Asaka K (2008) Ion Polymer Metal Compound Actuator for Active Phlegm Remover in Ventilator Circuit. Proc. 11th International Conference on New Actuators:523-526

[4] Nakamura T, Ihara T, Muka T, Asaka K, and Noritsugu,T (2008) Ion Polymer Metal Compound as a Power Assist Hand Sensor. Proc. 11th International Conference on New Actuators:981-984

[5] Ihara T, Nakamura T, Muka T, Asaka K (2007) Heat Press Process of Ion Polymer Metal Compound and its Generating Stress. Proc. 8th SICE System Integration Division Annual Conference:221-222

[6] Nakamura T, Ihara T, Muka T, Asaka K (2007) Water Content of Ion Polymer Metal Compound and its Sensor Characteristics. Proc. 8th SICE System Integration Division Annual Conference: 223-224

[7] Fujiwara N, Asaka K, Nishimura Y, Oguro K, and Torikai E (2000) Preparation of Gold-Solid Polymer Electrolyte Composites as Electric Stimuli-Responsive Materials. Chemistry of Material 12:1750-1754

[8] Fujiwara N, Asaka K, Y. Nishimura, Oguro K, Torikai E (2000) Preparation of Gold-Solid Electrolyte Composites as Electric Stimuli-Responsive Materials. Chem. Materials 12:1750-1754

[9] de Gennes PG, Okumura K, Shahinpoor M, Kim KJ (2000) Mechanoelectric effects in ionic gels. Europhysics Letters 50:513-518

[10] Newbury KM, and Leo DJ (2003) Linear Electromechanical Model of Ionic Polymer Transducers – Part I: Model Development, Journal of Intelligent Material Systems and Structures. 14:333-342

[11] Newbury KM, and Leo DJ (2003) Linear Electromechanical Model of Ionic Polymer Transducers – Part II: Experimental Validation. Journal of Intelligent Material Systems and Structures 14:343-357

[12] Asaka K, Oguro K, Nishimura Y, Mizuhata M, and Takenaka H (1995) Bending of Polyelectrolyte Membrane-Platinum Composites by Electric Stimuli I. Response Characteristics to Various Waveforms. Polymer Journal 27:436-440

[13] Asaka K, Oguro K (2000) Bending of Polyelectrolyte Membrane-Platinum Composites by Electric Stimuli Part II. Response Characteristics to Various Waveforms. Journal of Electroanalytical Chemistry 480:186-198

[14] Asaka K, Oguro K (2000) Bending of Polyelectrolyte Membrane-Platinum Composites by Electric Stimuli III: Self-Oscillation. Electrochim. Acta 45:4517-4523

[15] Ihara T, Nakamura T, Nakamura T, Ikada Y, Asaka K, Oguro K, Fujiwara N (2004) Application of a Solid Polymer Electrolyte Membrane-Gold to an Active Graft. Proceedings of the first International Congress on Biomimetics and Artificial Muscle 2:60-63

[16] K.Takagi, Nakabo Y, Luo ZW, Asaka K (2007) On a Distributed Parameter Model for Electrical Impedance of Ionic Polymer. Proc. SPIE 6524:652416;1-652416;8

[17] Kamamichi N, Stoimenov B, Mukai T, and Asaka K (2006) A Sensor-Actuator Integrated System with a Patterned IPMC — the interference of actuation to the sensing signal. SICE System Integration Division Annual Conference: 175-176

[18] Kim KJ, Shahinpoor M (2002) A novel method of manufacturing three-dimensional ionic polymer-metal composites (IPMCs) biomimetic sensors, and artificial muscles. Polymer 43:797-802

[19] Yamakita M, Kamamichi N, Kaneda Y, Asaka K and Luo ZW (2004) Development of an Artificial Muscle Linear Actuator Using Ionic Polymer-Metal Composites. Advanced Robotics 18:383-399

[20] Guo S, Okuda Y, Zhang W, Ye X, Asaka K (2006) The development of a hybrid type of underwater micro biped robot. J. Applied Bionics and Biomechanics 3:143-150

[21] Hitsumoto S, Ihara T, Morishima K (2007) Study on Cell Stimulating System using Micro fabricated IPMC. Proc. 8th SICE System Integration Division Annual Conference: 231-232